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On some problems concerning the seismic field methods.

By

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(With 5 figures.)

Zusammenfassung: Die Perioden der Longitudinalwellen, die bei künstlichen Explosionen erzeugt werden, nehmen nach einem ähnlichen Gesetz zu, wie die Perioden der Erdbebenwellen. In der Nähe der Sprengstelle sind daher die Einsätze der Wellen im allgemeinen schärfer. Die Amplituden können nach den für longitudinale Wellen gültigen Beziehungen berechnet werden. Fig. 1 zeigt das Ergebnis für direkte und reflektierte Wellen unter bestimmten Annahmen. Die Beobachtungen entsprechen qualitativ den berechneten Werten. Dies gilt auch für die gebrochenen Wellen, für deren Verlauf keinerlei mit der Theorie in Widerspruch stehende Annahmen gemacht werden müssen. In einer früheren Arbeit (4) wurde bereits gezeigt, daß die durch den mit der Tiefe wachsenden Druck bedingte Zunahme der Wellengeschwindigkeit eine Krümmung der Wellenbahn im tieferen Medium zur Folge haben muß, die die Wellen bei genügender Herddistanz von der Unstetigkeitsfläche wegführt. Eine Reihe von Beobachtungen zeigt, daß im allgemeinen diese Zunahme der Geschwindigkeit mit der Tiefe etwas größer ist, als ursprünglich aus den Experimenten über die Zunahme der elastischen Konstanten mit zunehmendem Druck geschlossen worden war. Bei Wellen, die in sehr alten Sedimenten oder in Granit verlaufen, bei denen die Zunahme der Wellengeschwindigkeit mit der Tiefe und daher auch die Strahlkrümmung gering sind, ist, wie theoretisch zu erwarten, eine große Energiemenge nötig, um die gebrochenen Wellen zu registrieren. — Weiterhin werden Näherungsformeln abgeleitet, die es ermöglichen, aus den bei einem Schuß von Instrumenten in verschiedenen Entfernungen aufgezeichneten reflektierten Wellen die Komponente des Fallwinkels in der betreffenden Richtung angenähert zu erhalten. Die Genauigkeit dieser Methode wird diskutiert und ein Beispiel gegeben. — Die bei künstlichen Explosionen registrierten Oberflächenwellen sind zu lang, um als in der obersten Schicht mit geringer Wellengeschwindigkeit verlaufende Wellen gedeutet werden zu können. Anderseits ist ihre Geschwindigkeit (250 bis

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400 m/sec, wenig abhängig vom Material) zu gering für Scheerungs- oder Rayleigh-Wellen in tieferen Schichten. Vielleicht handelt es sich um gravitationale Wellen in viskosen Medien, ähnlich den bei Erdbeben in der Nähe des Herdes manchmal gefühlten Oberflächenwellen.

Summary: The periods of longitudinal waves produced by explosions increase with distance in a similar way as earthquake waves (equation 1). The amplitudes of the waves (equation 1) depend not only on the amount of energy reflected or refracted at discontinuities, but also on the angle of incidence at the instruments and its rate of change with distance. Calculations on the relative amplitudes of direct, reflected and refracted waves (Fig. 1) are in agreement with the observations. Formulae are given to calculate the approximative dip of discontinuities using either the distance at which the travel time of the reflected wave is a minimum or the difference in travel time between two instruments, especially at two opposite sides of the shot point, or the direction of the travel time curve at the shot point. The surface waves (ground roll) recorded from explosions can hardly be pure elastic waves; their velocity is too small for either Love- or Rayleigh-waves.

I. Introductory.

During recent years experiments have been made by Dr. JOHN P. BUWALDA, professor of geology at the California Institute of Technology, and by the author to investigate the effectiveness of seismographic methods in the determination of the earths crustal structure. Preliminary results of these investigations have been published in most cases (1), and it is intended to present more detailed data in the near future. During these experiments, some theoretical problems have been investigated. Some of them have been presented at meetings (1, 2). The present paper gives some details on such problems of general theoretical interest.

II. On the periods of reflected waves.

In the neighborhood of the origin the periods of seismic waves increase with increasing distance. A large body of data concerning earthquake waves has been published recently by the author (3). In the case of waves produced by artificial explosions the following approximate formula had been found (4).

$$T^2 = T_0^2 + 0.0001\,D \tag{1}$$

where T is the period of the waves at the distance D (measured in km) from the source and T_0 the period of the waves close to the source. The results of recent experiments (see table 1) agree within the limits

Table 1. Periods of reflected waves in thousandths of a second at Semitropic Ridge, in the San Joaquin Valley, about 50 km northwest of Bakersfield, California. $\varDelta$ is the average distance between the shot point and the instruments in km, d the depth of the reflecting surface in km, ch the charge in pounds. The charge was exploded in a pipe, partly filled with water, at a depth of 60 feet (20 m).

	d	1.4	1.8	1.9	2.4	2.6	3.3	3.8	4.2	4.7	5.6
$\varDelta$	ch										
0.1	$3^{3}/_{4}$	—	—	—	3 ?	3	3	3	3	3	—
0.8	$1^{1}/_{4}$	—	2	2 ?	3 ?	—	—	—	—	—	—
	$3^{3}/_{4}$	—	—	—	—	$2^{3}/_{4}$	3	$2^{3}/_{4}$	3	$3^{1}/_{2}$	—
	5	—	—	—	—	—	$2^{1}/_{2}$	3	—	—	—
1.7	$1^{1}/_{4}$	2	$2^{1}/_{4}$	$2^{1}/_{2}$?	$3^{1}/_{4}$	$2^{3}/_{4}$	3	$2^{3}/_{4}$	3	—	$3^{3}/_{4}$?
	$3^{3}/_{4}$	—	—	—	—	—	3	$3^{1}/_{4}$	$3^{1}/_{4}$	4	—
2.5	$3^{3}/_{4}$	2	$2^{1}/_{4}$	$2^{1}/_{4}$	—	—	—	—	—	—	—
	10	—	—	$2^{1}/_{2}$	—	$2^{3}/_{4}$	3	3	$3^{1}/_{4}$	$3^{1}/_{2}$	4
3.3	10	—	2	2	3	3	—	—	$4^{1}/_{2}$	—	—
	25	—	—	2	$3^{1}/_{4}$	3	3	$3^{1}/_{2}$	$4^{1}/_{2}$	—	5

of error with equation (1). If we suppose a period T_0 of about 2 thousands of a second at the origin, the calculated values for $D = 5$ km and $D = 12$ km are 3 and 4 thousandths of a second respectively. These correspond very well to the values observed at long distances from reflecting depths at $2^{1}/_{2}$ and 5.6 km respectively (table 1). There is no noticeable influence of the charge on the periods.

The increase of the periods with increasing depth of the reflecting surface and with the increase in distance between instruments and shot point affects the sharpness of the beginning of the waves.

III. On the amplitudes of reflected and refracted waves.

The amplitude a of any wave at the distance D is given to a first approximation, neglecting the absorption, by

$$a = A \sqrt{F \frac{\tan i}{D} \frac{d i}{d D}} \tag{2}$$

where A is a factor depending on the component, the angle of incidence (i) and Poisson's ratio; F depends on the ratio of the velocities and densities and the angle of incidence at the discontinuities where the waves have been refracted or reflected. Data concerning A, and formulae to compute F were given for example in an earlier paper (4 on pp. 204—211). Fig. 1 shows the changes of amplitudes with distance computed for the direct wave (a) and reflected waves (b—f) on different suppositions. Though in general conditions will differ widely in different regions, the qualitative results in many cases will be of the same order as in Fig. 1.

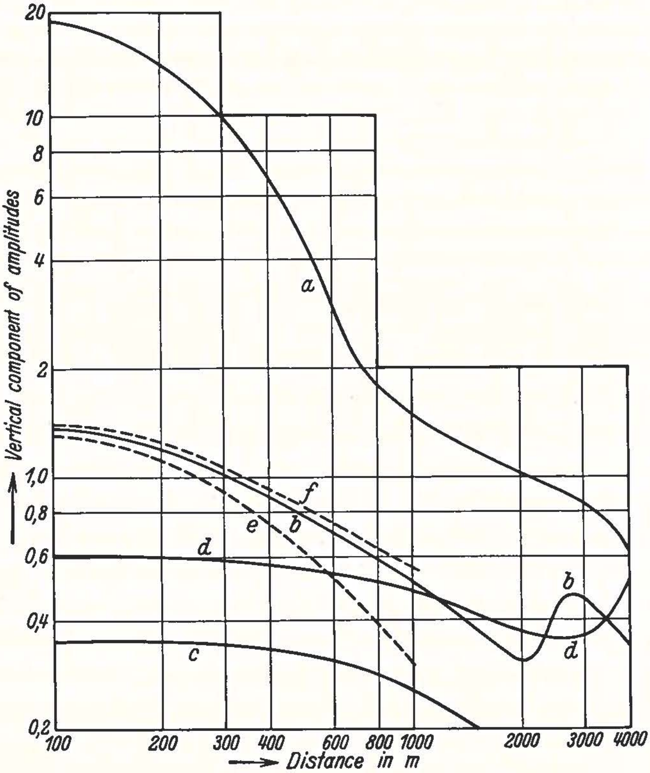

Fig. 1. Vertical component of amplitudes of direct (a) and reflected (b—f) waves from a source in the surface of a layer in which the velocity increases slowly with depth; calculated from formula (2). In the cases b, e, f the reflecting surface was assumed at a depth of 500 m, while the curves c and d were calculated on the assumption that the velocity increases gradually down to a discontinuity at a depth of 2000 m. The ratio of the velocities at the discontinuities is 1.1 in the cases b, c, e, f, and 1.3 in case d. The reflecting surface was assumed to be horizontal in b, c, d, and to have a dip of 10° in e and f, down from the shot point towards the instruments in e, and in the reverse direction in f.

If the first movement corresponds to a refracted wave, the relative amplitudes may be considerably smaller than those given by curve *a*, and occasionally even smaller than the amplitudes of reflected waves (see Fig. 3). The increase in amplitudes at large distances shown in *b* and *d* corresponds to the approach towards the critical angle of reflection at the discontinuity. Usually this increase occurs at too great a distance to be of advantage in field work.

The question how the energy is propagated in the case of refracted waves has been treated by several scientists. The author, in an earlier paper (4) has tried to show that the curvature of the rays due to the increase of velocity with depth explains the observations. The assumptions made in that earlier paper were based on the observed increase of the bulk moduli with increasing pressure. Now more exact observations are available. In our experiments (1) three cases are available where long refraction profiles have been secured: in the San Joaquin Valley, the Big Horn Basin and the Los Angeles Basin, the data permitted calculation of the velocities to a depth of about 2000 meters. On the other hand, the wave velocities in the corresponding layers have been measured at points, where these layers crop out, but below the "surface layer with low velocity". In the Los Angeles Basin the velocity increases at the refraction profiles from 1.9 km/sec at the surface (again neglecting the thin low velocity surface layer) to about $3^1/_2$ km/sec at a depth of 2000 meters. The velocity in all these layers where they are near the surface does scarcely exceed 2 km/sec. Similar values are correct for the San Joaquin Valley, where the velocity at a depth of 2000 meters is about 3 km/sec while the velocity in the same layer near the surface is somewhat less than 2 km/sec. In the Big Horn Basin, finally, the velocity along the refraction profile increased from 2.4 km/sec at the surface to about $4^1/_2$ km/sec at a depth of 2000 meters. The highest velocity which has been found close to the surface is less than 3 km/sec belonging very probably to a layer which is at a larger depth than 2000 meters at the refraction profile. In the earlier paper (4) (on p. 199) the assumption has been made that in the upper layers the increase of velocity with depth due to the increasing pressure may be approximately given by the form $v = a + b\,d$, where a and b are constants while d is the depth. From the results just mentioned we find that in the three cases this equation is approximately correct in the form $v = a\,(1 + {}^1/_3\,d)$ where all quantities are given in km and sec. In the case where the surface velocity is 2 km/sec, we have $v = 2 + {}^2/_3\,d$, which agrees within the limits of error with the values assumed on p. 200 of the earlier paper by using data from observations concerning the elastic constants but indicates a slightly faster increase of velocity with depth. The refracted waves, therefore, are even somewhat more curved than the calculations in that paper would indicate, and there is no need to make assumptions which contradict the theory of elastic waves in order to explain the phenomena observed with refracted waves. In a recent paper (8) M. MUSCAT has discussed the theory of refracted waves and has shown that the geometrical optics give an approximation accurate enough for all practical work at present.

We have seen that there is a large influence of pressure on the velocity in a given material. There are differences, on the other hand, of the same order between the velocities in different materials under the same pressure. During our investigations (1) we have found the following values for velocities of longitudinal waves (both columns concern the same layer):

	near the surface km/sec	at a depth of 2000 m km/sec
Gravel, dry sand	$^1/_2$—1	—
Wet sand	$^3/_4$—$1^1/_2$	—
Clay, alluvium or tertiary	$1^1/_4$—2	3—$3^1/_2$
Sandstone, cretaceous	2—$2^1/_2$	—
Triassic gypsum and red beds	$2^3/_4$—3	$\geqq 4^1/_2$
Old crystalline rocks, Frazier Mt.	4—$4^1/_4$	—
do. Beartooth Mt.	about $5^1/_2$	—
Granite, Yosemite	$5^1/_4$	$5^1/_2 \pm$

B. B. WEATHERBY and L. Y. FAUST (5) have recently published the following values of velocities of longitudinal waves:

Limestone	At the surface km/sec	At a depth of about 1200 m km/sec
Cretaceous	3.4	4.1
Permian	—	4.7
Pennsylvanian	4.6	4.7
Mississippian	3.8	5.2
Devonian	4.3	5.3
Ordovician	5.1	6.1

The data in the two columns do not concern the same layer and are, therefore, not exactly comparable. It must be borne in mind, besides, that the values differ considerably at different localities. In shale and sandstone they have found the following values:

	to 2000 feet (600 m) km/sec	2000—3000 feet (600—900 m) km/sec	3000—4000 feet (900—1200 m) km/sec
Pleistocene to Oligocene	2.0	2.2	2.5
Eocene	2.2	2.7	3.1
Cretaceous	2.3	2.8	3.3
Permian	2.6	3.3	—
Pennsylvanian	2.9	3.4	3.6
Devonian	4.1	4.1	4.1

The data of the three tables give a general idea about the velocities which are involved. They show, in agreement with the experiments on elastic constants, that the velocity increases only slightly with pressure in cases were the original velocity is high. As a consequence, in such material the curvature of the wave paths should be small, and the refracted waves through such layers should have small amplitudes (6). This theoretical result is confirmed by observations. While in material with small wave velocities relatively small amounts of dynamite are needed to produce large refracted waves in the seismograms at distances of a few kilometers, the amount of energy required to record waves refracted through granite is a large multiple of that in the first case. In Yosemite Valley, for example, the explosion of about 50 pounds of dynamite produced refracted waves through the granite which barely could be found at a distance of four km from the shot point. That this is not due to a large coefficient of absorption, follows from our experiments described on p. 230 of the earlier paper (4), where small amounts of dynamite exploded in the granite itself produced large direct waves. Similar results as to direct and refracted waves as well were found in other regions with granitic material.

In addition to their theoretical value which we have just mentioned, these results are of practical importance. We find that the velocity of the waves in a given material depends on the pressure and, therefore, on the depth. If a certain surface which we follow in our attempt to find its contour lines, approaches the surface of the earth, the factor with which we have to multiply the observed travel time of the reflected wave in order to find the depth of the surface decreases in a way depending on the material.

IV. The Dip of surfaces.

As was first pointed out by Henry Salvatori (7) it is possible to find the direction and the amount of the dip of a reflecting surface, within certain limits, because of the fact that the time intervals between the beginnings of the reflected waves recorded by the different instruments depend partly upon the dip of the discontinuity. "If . . . the velocity of propagation is accurately known, and two determinations are made at each shot position with the seismometers placed along two lines in opposite directions from the shot point, the angle of dip of the reflecting beds may be determined by this method with an accuracy of about 2°". Unless a constant average velocity between the surface and the reflecting discontinuity can be assumed, the exact formulae are very complicated, and if there exist two or more layers, the dip α, in general, cannot be calculated exactly from the observed travel times of the reflected waves. Salvatori therefore, suggests making the computations, in actual routine practice, by means of charts, plotted from figures calculated in the office in a manner involving no approximations.

There is no doubt that the considerable time spent in following out Salvatori's suggestions and making these calculations for a particular region is worth the labor only when very much shooting is to be done there. Otherwise, and for rapid preliminary work in the field, we may assume an average, constant velocity v between the surface of the earth and the reflecting surface. In Fig. 2, S is the shot point, I its image point relative to the reflecting surface. From the figure we find the following equations supposing that we are shooting in the direction of the maximum dip:

$$S I = 2 S B = 2 d \cos \alpha ,$$

where d is the depth of the reflecting surface under the shot point;

$$\Delta^* = 2 d \cos \alpha \sin \alpha = d \sin 2 \alpha \qquad h = S B = d \cos \alpha$$

$$d = h / \cos \alpha \tag{3}$$

$$S M N = I M N = \sqrt{a^2 + D^2} .$$

The travel time t_1 of a reflected wave along the path $S\,M\,N$ is

$$t = \frac{\sqrt{a^2 + D^2}}{V}. \tag{4}$$

If we observe the travel time t_1 of a reflected wave at the distance Δ_1 of one instrument and the travel time t_2 at the distance Δ_2 of another instrument, we find

$$v^2\,(t_2{}^2 - t_1{}^2) = D_2{}^2 - D_1{}^2 = (D_2 + D_1)\,(D_2 - D_1)\,.$$

From the figure we see that $D_2 + D_1 = \Delta_2 + \Delta_1 - 2\,\Delta^* = 2\,\Delta_m - 2\,\Delta^*$ where $\Delta^* = S\,A\,, \quad I\,A \perp S\,N.$

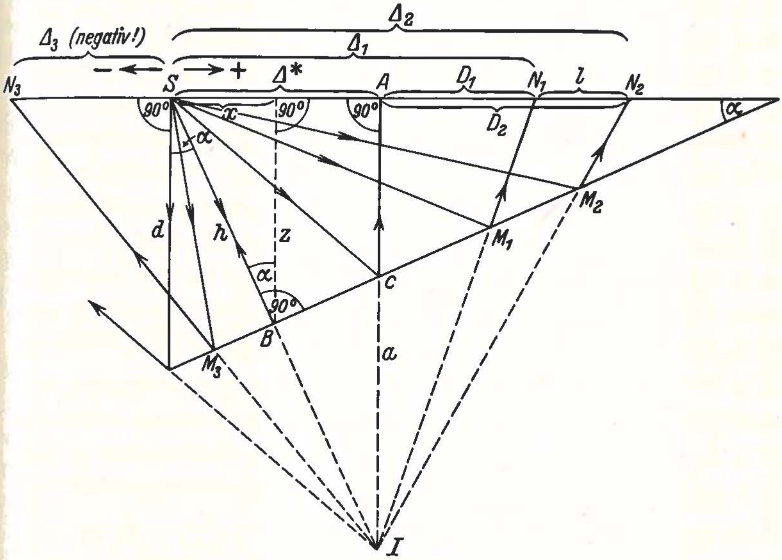

Fig. 2.

Δ_m is the average distance of the two instruments from the shot point. Δ is taken as negative in the direction of the dip, and therefore (see equation 3) α is negative in the same direction. We introduce

$l = D_2 - D_1$, the distance between the two instruments,

$t_m = \frac{1}{2}\,(t_2 + t_1)$, the average travel time to the two instruments,

$t_d = (t_2 - t_1)$, the difference in the times of arrival of the reflected wave at the two instruments, and we find

$$v^2\,(t_2{}^2 - t_1{}^2) = 2\,v^2\,t_m\,t_d = 2\,l\,(\Delta_m - \Delta^*) \quad \text{or} \quad \Delta^* = \Delta_m - \frac{v^2\,t_m\,t_d}{l}$$

Introducing, finally, the values of Δ^* and d from the equations (3), we find

$$\sin 2\alpha = \frac{1}{d}\left(\Delta_m - \frac{v^2 t_m t_d}{l}\right) \quad \text{or} \quad \sin\alpha = \frac{1}{2h}\left(\Delta_m - \frac{v^2 t_m t_d}{l}\right) \tag{5}$$

Along the path $S\,B\,S$ we have $h = {}^1/_2\, t_0 v$, and therefore equation (5) may be written in the form

$$\sin\alpha = \frac{\Delta_m}{2h} - \frac{v\,t_d}{l}\,\frac{t_m}{t_0} = \frac{\Delta_m}{t_0 v} - \frac{v\,t_d}{l}\,\frac{t_m}{t_0} \tag{6}$$

The last term t_m/t_0 is usually small and can be neglected in most cases. If v is known, the dip α can be calculated from equation (6). In the second term of this equation, t_d is to be taken positive, if the instrument closer to the shot point records the reflection earlier then the more distant instrument. If the resulting α is positive, the reflecting surface is closer to the surface of the earth under the instruments than under the shot point. $\sin\alpha$ changes by about 0.015 per degree if $\alpha < 40^0$. If a difference in t_d of 0.001^s shall correspond to a difference of about 1^0 in α, we find from (6) that 0.001 v/l must be about 0.015, if the instruments are close to the shot point, or l must be about $v/15$. If, for example, $v = 3$ km/sec, the spread l of the instruments must be about 200 meters or about 600 feet.

In these experiments the effect of the differences in the uppermost layer with low velocity must be determined very exactly, as they occasionally produce differences in the time of arrival of the reflected waves by many thousands of a second at the various instruments.

From Fig. 2 we see that that the reflected waves must have a minimum travel time at the distance Δ^*, as $A\,C\,A = I\,C\,A$ corresponds to the shortest path. At this distance

$$t_d = 0, \text{ and } \sin\alpha = \Delta^*/2\,h = \Delta^*/t_0\,v \tag{7}$$

If the dip is small, it quite often happens that Δ^* is within the range of distance at which the instruments are recording. In this case one of them records the reflected waves earlier than all others, and the dip may be found from (7).

If the dip is large, it can not be calculated exactly, as in this case the equations are no longer correct, especially, if Δ_m is large; besides, the point of reflection, at which the dip is found, is far away from the shot point (at the distance h sin α), and the dip may change with distance. The errors introduced by our assumptions have a minimum at the shot point. It is usually useful to place the instruments equidistant in opposite directions from the shot point (see Fig. 5). In this case

$$\Delta_m = 0\,, \quad t_m = t_0\,,$$
$$\sin \alpha = -v\, t_d/l =$$
$$-v\,[d\,t/d\,\Delta]_{\Delta=0}, \quad (8)$$

and the error introduced in assuming the velocity v is relatively small. If the reflecting layers are parallel, v is equal to the velocity in the upper layer. In other cases it has a larger value depending on the conditions.

In shooting in the direction of the strike, the reflection takes place at a distance $x = h \sin \alpha$ from the shot point in the direction where the discontinuity approaches the surface of the earth. Its depth there is $h \cos \alpha = \frac{1}{2} t_0\, v \cos \alpha$. If it is a plane, its depth under the shot point is

$$h/\cos \alpha = \frac{1}{2}\, t_0\, v/\cos \alpha.$$

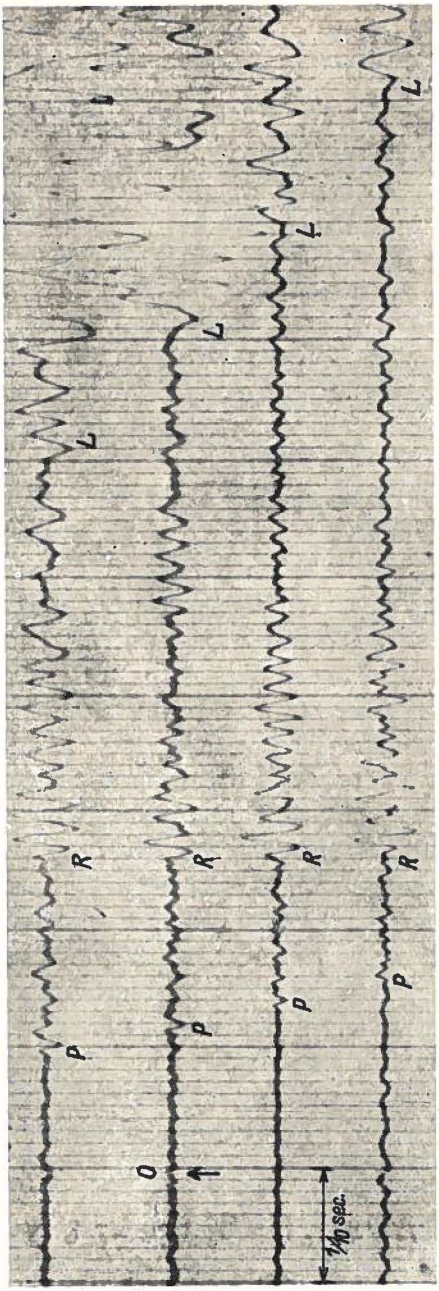

Fig. 3. Seismogram, recorded by the outfit of the California Institute of Technology, built by Dr. H. Benioff. 1/8 pound of 60% dynamite was exploded at a depth of 3 feet. Sensitivity of the instruments 15% of normal. P are refracted waves, R reflected waves and L the beginning of the surface waves.

As an example we take the seismogram reproduced in Fig. 3 and a similar seismogram (not reproduced here) which was recorded at the same shot point, but in an opposite direction. The following travel times have been read for the main reflection, marked by "R" in Fig. 3:

	instruments north				south (Fig. 3)				
distance	297	266	232	199	182	209	244	276	meters
time	0.350	0.340	0.327	0.318	0.260	0.261	0.262	0.264	sec.

From the observations we find

north		south	
$\Delta_m = 248$ m	$t_m = 0.388$ sec	$\Delta_m = 229$ m	$t_m = 0.262$ sec
$l = 98$ m	$t_d = 0.040$ sec	$l = 94$ m	$t_d = 0.004$ sec.

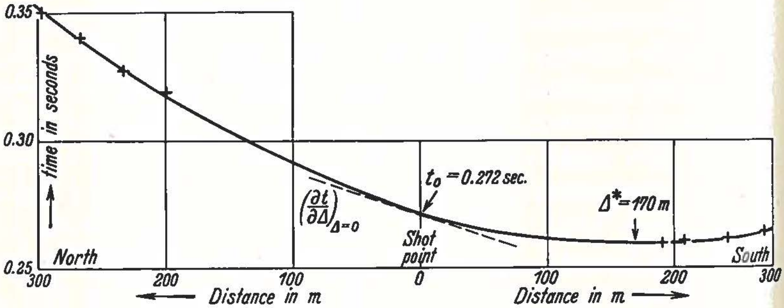

Fig. 4.

From a refraction profile, two layers have been found overlying the discontinuity from which we recorded the reflected waves. The average velocity in these layers is 1.9 km/sec; for more exact results the two layers, one with a velocity of 1.65 and one with 2.0 km/sec, could be treated separately. If we plot the measurements (fig. 4), wo find at the shot point the time of reflection $t_0 = 0{,}272$ sec. Usually this can be found accurately enough without plotting the data. This gives $h = (1.9/2) \times 0.272 = 260$ meters. As may be seen from Fig. 3, the distance Δ^* of the point with the minimum time of reflection is very close to the first instrument at the southern position. From figure 4 we see that $\Delta^* =$ ca. 170 meters. Finally, we have at the shot point $dt/d\Delta =$ ca $0.010/0.065$ sec/km. Using equation (5) and the values obtained with the instruments north, we find under the supposition that our instruments were arranged in the direction of the maximum dip

$$\sin\alpha = \frac{1}{0.52}\left[0.248 - \frac{3.6\times 0.338\times 0.032}{0.098}\right] = -0{,}29; \qquad \alpha = 17^0 \text{ north}$$

and in a similar way, using the arrival times at the position south,

$$\sin\alpha = \frac{1}{0.52}\left[0.229 - \frac{3.6\times 0.262\times 0.004}{0.094}\right] = +0.36; \qquad \alpha = 21^0 \text{ north}$$

from equation (7) we find $\sin\alpha = 0.17/0.52 = 0{,}33$; $\alpha = 19^0$ north

and from equation (8): $\sin\alpha = 1.9/6.5 = 0.29$; $\alpha = 17^0$ north.

Average: $\alpha = 19^0$ north. Finally $h \sin\alpha = 260 \times 0{,}326 = 85$ m south, and the depth d_x there is $d_x = h\cos\alpha = 260 \times 0.946 = 250$ meters. The reflecting surface, therefore, is at a depth of 250 meters at a distance 85 meters south of the shot point and has a component of dip there of about 19^0 towards north. The differences in the resulting values of α are partly due to the errors in reading, partly due to the approximations in the formulae and partly due to the fact that the reflecting surface probably is not a plane. From figure 4 it is obvious that more instruments would have given more exact data in a shorter time. (Recording sets with 12 and more traces are generally used now for this reason. See Fig. 5 p. 138).

To get the maximum dip and its direction, reflections must be secured in different directions. Experiments have shown that in the case of nearly horizontal surfaces the arrival times of the reflected waves agree very well with the instruments oriented in different directions from the shot point. Occasionally the conditions which are favorable to good reflections differ somewhat in different directions; in case of failure in getting reflections in one direction, better results occasionally may be obtained in another. In case of a very large dip, it is favorable to use in at least one shot such an orientation of the instruments that the line through the instruments and the shot point is parallel to the strike of the reflecting surface in order to find the reflections more easily and to space the instruments very closely in shooting in the direction of the dip. In general the reflections come out clearest if there is a slight dip of the discontinuity down from the instruments towards the shot point, as in this case the reflections occur nearly simultaneously and usually are very sharp. If the dip is not very large, no considerable effect on the amplitudes of the reflected waves is to be expected. (Compare curves e and f in Fig. 1.)

V. On the surface waves produced by explosions.

Surface waves are by definition only such waves in which the energy is propagated mainly along a discontinuity, in our case along the surface

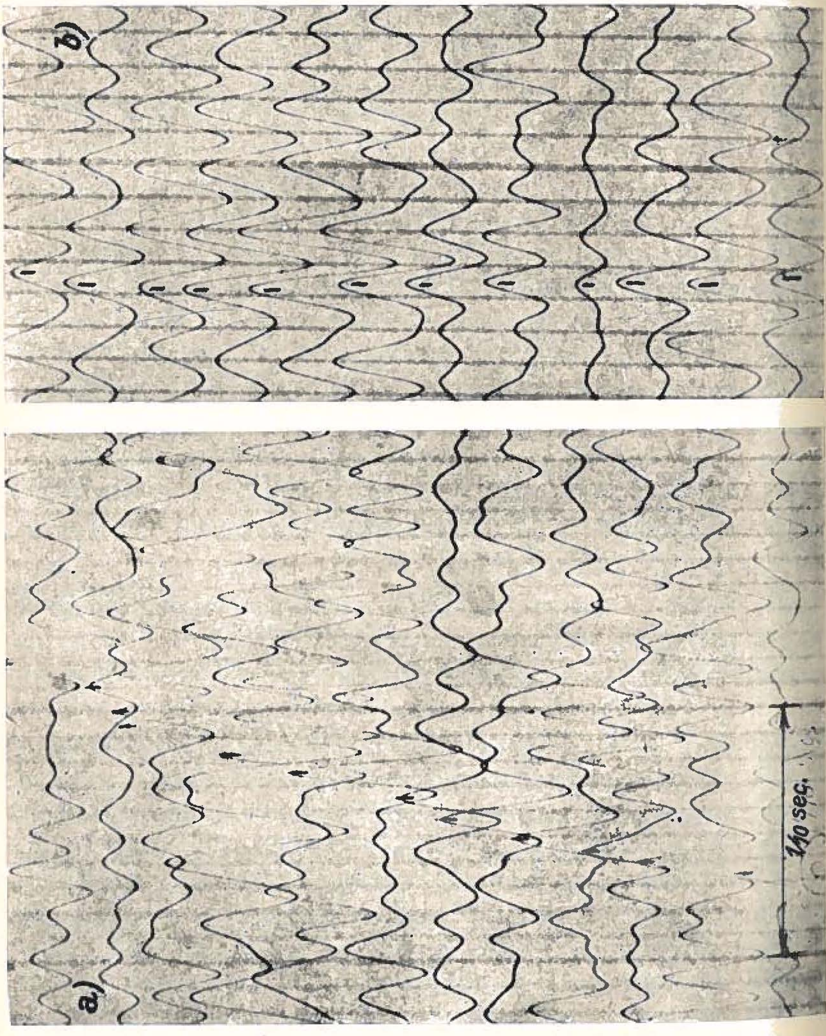

Fig. 5. Seismograms recorded by Dr. J. Soske and Dr. R. Peterson with the new outfit of the California Institute of Technology. Spread of the instruments about 1500 feet (450 m), shot point between instruments 6 and 7. Charge 9 pounds of $60^0/_0$ dynamite, exploded at a depth of 75 feet (about 23 m). a) reflection from a surface with large dip, b) reflection from a surface with small dip at another shot point.

of the earth, and in which the amplitude decreases exponentially with an increasing distance from the discontinuity. These surface waves are called "ground waves" or "ground roll" by some geophysicists. Others apply the expression "surface waves" to the longitudinal waves which are propagated close to the surface if the distance between the source and the instrument is not large. This procedure is incorrect, as these waves are not conditioned by the surface and as they travel many wave lengths beneath the surface, if the distance between the shot point and the instrument is large enough.

The amplitudes of the surface waves are proportional to $e^{-kd/L}$ to a first approximation, where k is a constant depending on the type of surface waves and the material in which they are propagated, L the wave length and d the depth at which the charge is exploded. Usually explosions at depths between 50 and 60 feet (about 15—20 m) do not produce considerable surface waves; they may be troublesome at the same place, when the charge is exploded at a depth of about 30 feet (10 m). In very hard rock they are frequently small even when the explosion takes place at a depth of a very few feet.

In an earlier paper (4) some results on observed surface waves have been published. The recent experiments have confirmed the previous results. Whenever it was possible to feel the surface waves, they arrived about at the same time as the sound waves through the air, sometimes a fraction of a second later, sometimes earlier. As the same is true in the case of the recorded waves, which are for example clearly recorded in Fig. 3 ("L"), there is no doubt that these felt waves are the same as the "ground roll". Their velocity, in general, is between 250 and 400 m/sec. No clear connection could be found between the velocity of these waves and the velocity of longitudinal waves in the same region, and no explanation for them can be offered assuming that they are pure elastic waves. Their periods are of the order of 0,1 sec; their wave lengths (usually between 10 and 50 m) are too large for vibrations of a thin layer with small velocity of longitudinal waves. Their velocity seems to depend little on the elastic constants of the material and is too small for Rayleigh or shear waves in a thicker layer. Their amplitudes decrease very fast with distance. They may correspond to the surface waves observed by people in the epicentral region of an earthquake and may be of a gravitational type of surface waves in a viscous medium.

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